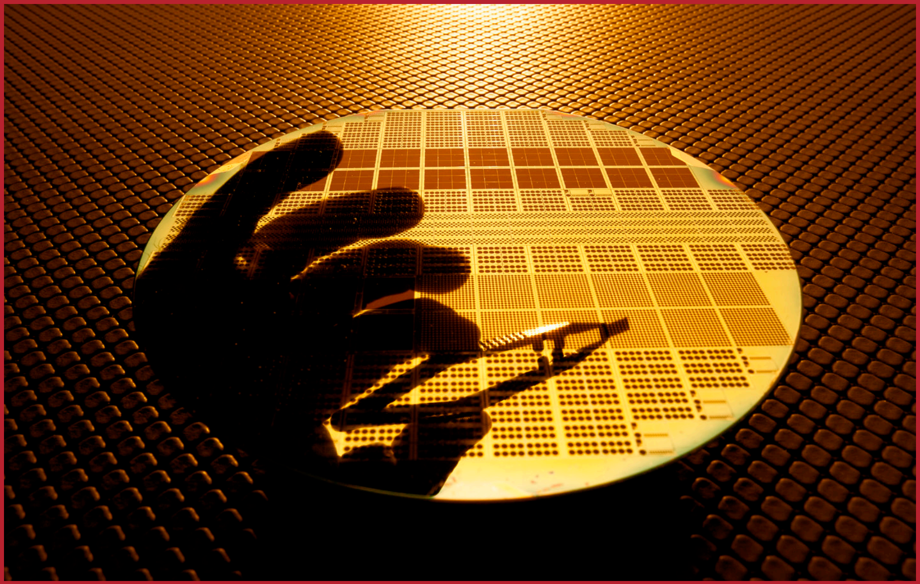
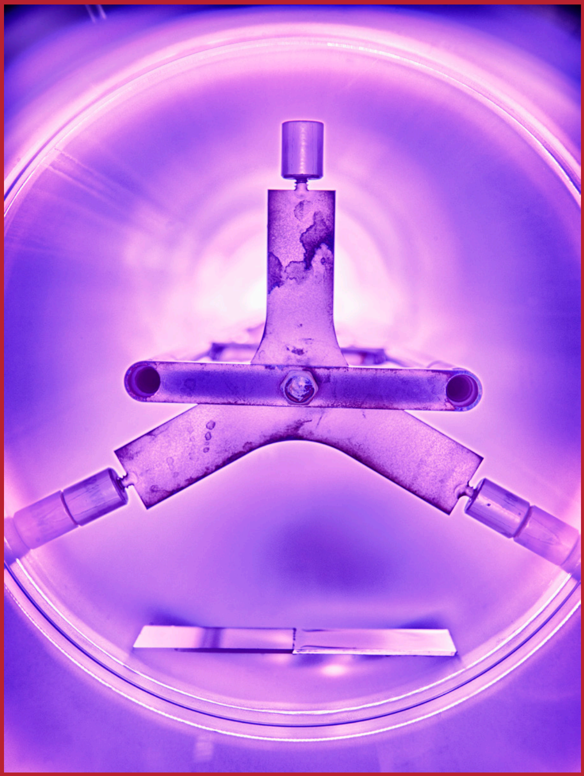
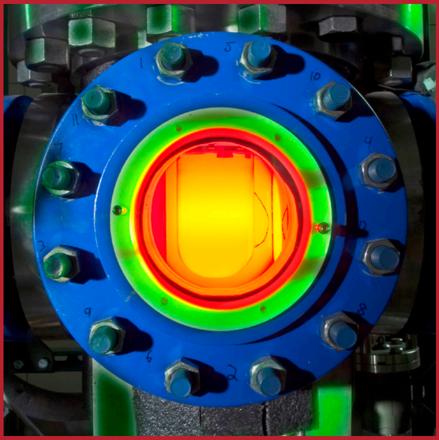
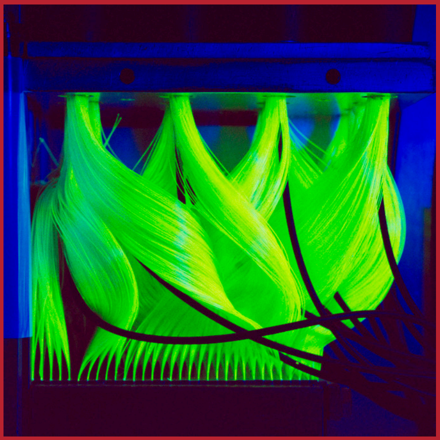
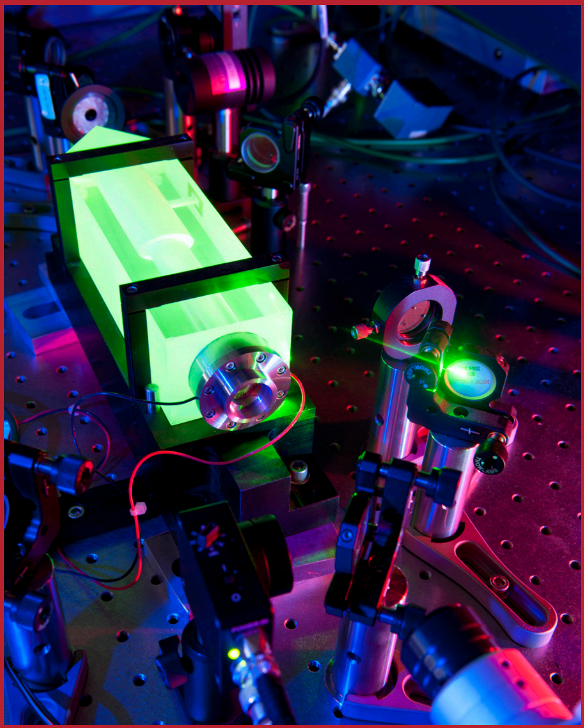
2016 Fermilab | Laboratory Directed Research & Development Annual Report

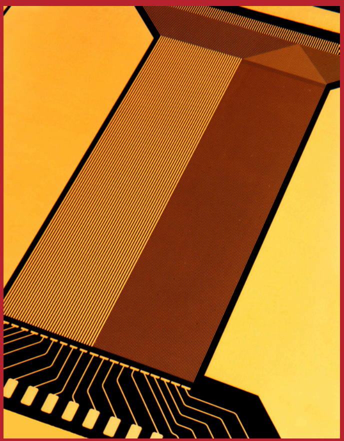












Fermilab

U.S. DEPARTMENT OF ENERGY | Office of Science

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I. Executive Summary

The Fermi National Accelerator Laboratory (FNAL) is conducting a Laboratory Directed Research and Development (LDRD) program. Fiscal year 2016 represents the second full year of LDRD at Fermilab and includes seven projects approved mid-year in FY14, six projects approved in FY15, and seven approved projects in FY16. Of these 20 projects, six have been completed. The implementation of LDRD at Fermilab is captured in the approved Fermilab 2016 LDRD Annual Program Plan. In FY16, the LDRD program represents 1.0% ($3.3M) of Laboratory funding. The scope of the LDRD program at Fermilab will be established over the next couple of years where a portfolio of about 20 on-going projects representing approximately between 1% and 2% of the Laboratory funding is anticipated.

This Annual Report focuses on the status of the current projects and provides an overview of the current status of LDRD at Fermilab. LDRD projects are generally initiated through a response to a Call for Proposals. The response has been outstanding to the three Calls for Proposals with 118 new ideas put forward resulting in 51 full proposals being submitted to a Selection Committee. After recommendations by the Selection Committee, the Laboratory Director has approved funding for twenty projects. Of those, fourteen are on-going projects that are the subject of this Annual Report.

All indications are that LDRD is improving the scientific and technical vitality of the Laboratory and providing new, novel, or cutting edge projects carried out at the forefront of science and technology. The projects are aligned with the core capabilities of Fermilab and hence are positioned to carry out the mission and strategic visions of Fermilab and the Department of Energy.

Operated by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the United States Department of Energy.

II. Program Overview

Beginning in FY 2014, Fermilab has initiated a LDRD program as authorized by a DOE order, now DOE O 413.2C, to enhance and realize the mission of the laboratory in a manner that also supports the laboratory's strategic objectives and the mission of the Department of Energy. LDRD funds enable scientific creativity, allow for exploration of "high risk, high payoff" research, and allow for the demonstration of new ideas, technical concepts, and devices. LDRD also has an objective of maintaining and enhancing the scientific and technical vitality of Fermilab.

LDRD is able to fund employee-initiated proposals that address the current strategic objectives and better position Fermilab for future mission needs. The request for such funds is made in consideration of the investment needs, affordability, and directives from DOE and Congress. Our implementation of LDRD also allows for the Laboratory Director, for instance, initiating a proposal from a Principal Investigator (PI) who is a strategic hire or otherwise working in a strategically important area.

The FY 2016 Fermilab Annual LDRD Program Plan has been used to implement the FY 2016 LDRD Program. The laboratory sought and was granted approval for an LDRD expenditure comprising up to a maximum of 1.6% ($4.5M) of the laboratory's total operating / capital budget. Actual expenditures were below the allowed maximum and came in at 1.0% ($3.3M) of the laboratory's total operating / capital budget. Being below the maximum allowed was due in part to alleviate budgetary pressure on other parts of the Fermilab program and the fact that projects generally have spent below initial maximum approved amounts as those often include project contingencies.

Following an approved FY 2016 Annual LDRD Program Plan, a call for proposals was issued and 34 preliminary proposals were received. These preliminary proposals were typically one or two pages in length and required supervisory and divisional concurrence as to the proposed scope of effort and materials. An LDRD Selection Committee reviewed these preliminary proposals and PI's were advised of their approximate competitive standing along with feedback should they wish to submit a full proposal.

In response to the preliminary proposal stage, a total of 15 full proposals were prepared, submitted, and fully evaluated by the LDRD Selection Committee. Each PI made a brief presentation to the Selection Committee. The LDRD Selection Committee evaluated the full proposals on a 5-point rating scale across 10 scoring criteria. The scoring criteria included an evaluation of the scientific or technical significance, innovativeness / novelty, the qualifications of the PI, the overall quality of the proposal, the likelihood of success, mission relevance, and relevance to the initiative as spelled out in the call for proposals, the strategic fit, enduring capability, and the likelihood to enhance the laboratory's reputation. In short, the scoring criteria encapsulated the key objectives and aspects that LDRD has as its purpose.

In consideration of the scope of proposals received, the LDRD selection committee made a recommendation to the Laboratory Director who approved the funding of the seven new

LDRD projects at Fermilab. Table 1 shows the flow down for proposals and funded projects for FY14, FY15, and FY16.

Table 1: Number of LDRD proposals received in response to the annual Call for Proposals, the number of full proposals prepared, and the number of awarded and funded LDRD Projects

Fiscal Year	Preliminary Proposals	Full Proposals	Funded LDRD Projects	Completed by Oct 2017
FY14	50	29	7	4
FY15	34	12	6	2
FY16	34	15	7	-

The twenty LDRD approved projects have internal laboratory project and task numbers assigned with budgetary information recorded such that financial tracking of effort and spending could be monitored. On roughly a monthly basis, project financial information is compiled, shared with the PI and the LDRD Coordinator. Each PI has also been asked to provide a short progress report to the LDRD Coordinator on approximately a monthly basis. In December 2014, August 2015, and August 2016, the LDRD selection committee conducted mid-year reviews of each of projects and recommended project continuation that was subsequently approved by the Laboratory Director. At the August mid-year review, the PI provided updated budget information for the following fiscal year. Each PI provided the Project Summary contained within this document with minor edits applied. The six completed projects will have a separate write-up as the Final Report of each project and only a brief description of each of these projects appears in this Report.

III. LDRD and Laboratory and Agency Mission

Department of Energy Mission

The mission of the Energy Department is to ensure America's security and prosperity by addressing its energy, environmental and nuclear challenges through transformative science and technology solutions.

Fermilab Mission

Our mission is to drive discovery in particle physics by

- *building and operating world-leading accelerator and detector facilities*
- *performing pioneering research with global partners*
- *developing new technologies for science that support U.S. industrial competetiveness*

The Mission statement of Fermilab reflects the pursuit of excellence in scientific research in the area of particle physics. Particle physics addresses scientific mysteries in matter, energy, space and time through cosmic science, Large Hadron Collider (LHC) science, neutrino science, and precision science. In addition to particle physics, Fermilab has core capabilities in accelerator science and technology, advanced computer science, and large-scale user facilities. Fermilab's Mission statement reflects Fermilab's role in support of the overall mission of the Department of Energy. In particular, "transformative science and technology solutions" in the area of particle physics will be furthered through the use of LDRD. LDRD provides flexibility and efficiency that enables investigators to carry out creative new projects in forefront areas that enrich the current Fermilab program and strategically put Fermilab in a better position to deliver the mission objectives of DOE and Fermilab for the future. The Project Summaries describe the relevance of each project to the missions of Fermilab and DOE.

IV. Summary of Fermilab LDRD Costs

The costs associated with the Fermilab LDRD program are reported as part of the annual CFO database upload required at the beginning of each fiscal year. Costs associated with the administration of LDRD are absorbed into the Laboratory's overhead. Table 2 shows a list of projects approved in FY14 and the spending for each project during FY16. Table 3 and 4 show the similar list of projects approved in FY15 and FY16.

Table 2: List of FY14 Fermilab LDRD Projects and the associated spending with each project. Shown is the actual spending in FY15 and uploaded to the CFO database.

LDRD Project FNAL-LDRD-	Project Name	FY2016 Spending	Completed
2014-010	Cosmic Microwave Background Detector Development at Fermilab	$773,106	
2014-012	Development of HTS Based Rapid-Cycling Accelerator Magnets	$154,586	
2014-016	High Frequency Gallium Nitride Driver	$58,288	*
2014-025	The Sinuous Target	$112,227	
2014-027	From Magic to Method: Characterizing High Voltage in Liquid Argon Time Projection Chambers with the Breakdown in liquid argon cryostat for high voltage experiments	$(-5,884)	*
2014-028	Deployment and operation of prototype CCD array at Reactor Site for detection of Coherent Neutrino-Nucleus Interaction	2,057	*
2014-038	Application-Oriented Network Traffic Analysis based on Graphical Processing Units	190,222	*
"FY14 Project" Totals		**$1,284,601**	

Note: FNAL-LDRD-2014-027 was completed early in FY16. A correction was required to account from an earlier labor charge mistakenly charged to the project. The net result is shown in the table as a negative amount for FY2016 spending.

Table 3: List of FY15 Fermilab LDRD Projects and the associated spending with each project. Shown is the actual spending in FY16 and uploaded to the CFO database.

LDRD Project FNAL-LDRD-	Project Name	FY2016 Spending	Completed
2015-009	High Energy Physics Pattern Recognition with an Automata Processor	$230,073	
2015-010	Dark Energy Survey and Gravitational Waves	$155,644	*
2015-020	Off-the-Shelf Data Acquisition System	$173,978	
2015-021	Transverse and Longitudinal Profile Diagnostics for H- Beams using Fiber Lasers and Synchronous Detection	$33,961	
2015-029	Nb_3Sn Superconducting RF Cavities to Reach Gradients up to 90MV/m and Enable 4.2K Operation of Accelerators	$695,079	*
2015-031	A Comprehensive Investigation of a Transformational Integrable Optics Test Storage Ring as a "Smart" Rapid Cycling Synchrotron for High-Intensity Beams	$110,171	
"FY15 Project" Totals		**$1,288,735**	

Table 4: List of FY16 Fermilab LDRD Projects and the associated spending with each project. Shown is the actual spending in FY16 and uploaded to the CFO database. The total FY2016 spending for all on-going projects (FY14+FY15+FY16) is also shown.

LDRD Project FNAL-LDRD-	Project Name	FY2016 Spending	Completed
2016-001	Beam Precision Time Profile Monitor	$69,559	
2016-004	Development of an ultra low energy threshold particle detector	$72,237	
2016-007	Tuning Axion Detectors with Non-Linear Dielectrics	$123,406	
2016-008	Novel Methods for High Performance Superconducting Coating on Copper	$97,993	
2016-010	Preparing HEP reconstruction and analysis software for exascale era computing	$189,465	
2016-032	Implement open source HEP NoSQL database	$46,206	
2016-034	Instrumentation for the Initial set of Critical Scientific Experiments in IOTA and the FAST Injector	$0	*Project will begin in FY17*
"FY16 Project" Totals		**$598,886**	
FY16 Total	*includes FY14-FY16 projects*	**$3,282,372**	

V. Project Summaries

Each of the thirteen on-going LDRD projects are described in the following Project Summaries. The project number and title, key authors including the PI are listed. A short project description is provided along with a statement addressing the relevance of the project to the Laboratory. A description follows of initial results and accomplishments along with a list of publications (if any) that have been produced.

Project Number and Title: FNAL-LDRD-2014-010
Cosmic Microwave Background (CMB) Detector Development at Fermilab

Authors: (PI) Bradford A. Benson (Fermilab); John Carlstrom (University of Chicago), Clarence Chang (Argonne National Lab), Hogan Nguyen (Fermilab)

Project Description:
This project proposes to establish capabilities at the Silicon Detector Facility (Sidet) at Fermilab to develop arrays of superconducting transition-edge sensors (TES) detectors for future CMB experiments. This proposal supports the design and development of new TES detector technologies, the assembly of prototype modules of TES detector arrays, and the construction of a unique high-throughput testing facility, to characterize large arrays of detectors for future CMB experiments.

Relevance:
Fully realizing the scientific potential of CMB polarization will require new detector technology that enables instruments with >10 times more sensitivity than current experiments. The technological challenges for future CMB experiments are well-matched to, and solely filled by national labs like Fermilab. This proposal explicitly follows the P5 report's recommendation to: "***Increase particle physics funding of CMB research and projects in the context of continued multiagency partnerships***." The instrumentation developed will lead to CMB experiments that aim to answer some of the most exciting questions in cosmology and that are at the heart of the high-energy physics mission: to constrain inflationary physics at grand-unified theory energy scales ($\sim 10^{16}$ GeV), to measure the sum of the neutrino masses at a level below the minimum mass expected from neutrino oscillations (< 0.06 eV), and to precisely constrain the relativistic energy density of the universe and any "dark radiation" component.

Results and Accomplishments:
In FY16, this proposal helped fund the development of new capabilities at the Silicon Detector Facility (Sidet) at Fermilab, and achieved several milestones in CMB related detector research and development. These included:

1) The purchase and cryogenic commissioning of a new detector test cryostat in Lab A at Sidet, capable of achieving a 50 mK base temperature using an adiabatic de-magnetization refridgerator (ADR). In FY17, this cryostat will be outfitted to further characterize CMB detectors, including: the installation of new cryogenic

wiring, which will enable the readout of ~6000 transition edge sensor (TES) detectors, and a new sub-Kelvin mechanical stage.

2) Tested over a dozen prototype CMB detector wafers, with ~2700 TES detectors / wafer, in existing He3-based cryostat in Lab A at Sidet, commissioned in FY16 via this LDRD.
3) The packaging and wire-bonding of over 30 prototype CMB-detector arrays fabricated at ANL, a process developed in FY14 as part of this LDRD, in support of a joint R&D effort to develop detector arrays for next-generation CMB experiments.
4) The packaging and wire-bonding of over 200 prototype superconducting inductor-capacitor (LC) chips, used to test a new 64x SQUID multiplexing system being developed.
5) Tested the spectral response of fourteen CMB detector wafers using a fourier transform spectrometer (FTS) built in FY15 via this LDRD, designed with high-throughput to enable more efficient characterization the mm-wave spectral response of prototype CMB detector arrays.
6) Continued efforts by Fermilab scientists and technicians to simulate and design prototype antenna-coupled TES detectors.

Publications:

1) "Optimization of Transition Edge Sensor Arrays for Cosmic Microwave Background Observations with the South Pole Telescope", Ding, J., et al., IEEE Transactions on Applied Superconductivity, Volume 27, Issue 4 (2017)
2) "Large Arrays of Dual-Polarized Multichroic TES detectors for CMB Measurements with the SPT-3G Receiver", Posada, C.M., et al., SPIE Proceedings, Volume 9914 (2016)
3) "Integrated Performance of a Frequency Domain Multiplexing Readout in the SPT-3G Receiver", SPIE Proceedings, Volume 9914 (2016)
4) "Low Loss Superconducting Microstrip Development at Argonne National Lab", Chang, C.L., et al., IEEE Transactions on Applied Superconductivity, Volume 25, Issue 3 (2015)
5) "Fabrication of large dual-polarized multichroic TES bolometer arrays for CMB measurements with the SPT-3G camera", Posada, C.M., et al., Superconductor Science and Technology, Volume 28, Number 9 (2015)
6) Benson, B. A., Ade, P. A. R., Ahmed, Z., et al. 2014, "SPT-3G: A Next-Generation Cosmic Microwave Background Polarization Experiment on the South Pole Telescope", Proceedings of the SPIE, 9153, 91531P

Project Number and Title: FNAL-LDRD-2014-012
Development of HTS Based Rapid-Cycling Accelerator Magnets

Authors: (PI) Henryk Piekarz, James Blowers and Steven Hays

Project description:
The goal is design, fabrication and test of short-sample rapid-cycling superconducting accelerator magnets using the combined novel power cable and core designs. The power

cables use high temperature superconductors (HTS) operating at the temperatures well below their superconductivity limit in order to expand the working temperature margin and in this way facilitate both prevention and detection of the cable quench. The temperature sensors are embedded in the liquid helium coolant flowing through the conductor former pipe. Two types of the power cable will be tested: A - Multiple wide YBCO tape strands stacked vertically and embedded inside the helium channel pipe, and B - Multiple very narrow YBCO strands wounded helically over the former pipe carrying the liquid helium coolant. The two cable designs differ in a way they minimize the power losses caused by the self-field coupling and the screen currents but also in the complexity of cable assembly work. The goal is to determine if the simpler and less expensive cable B assembly provides also satisfactory power losses.

Two types of magnetic cores will be used, one is the standard window-frame core with power cable running parallel on both sides of the beam gap and the second one is a novel design of a dual C-shaped magnetic core with two beam gaps in the vertical orientation and the power cable running in the vertical plane. The novel type magnet allows simultaneously accelerate two beams with a single power system and thus effectively doubling the beam intensity at only a modest cost increase due to a larger core mass. In addition, the beam losses as well as the beam particle decays are emitted into an open space away from the power cable thus strongly minimizing possibility of the radiation induced damage. Both these HTS cable types can be used with either of the magnetic core designs. For the LDRD_012 Proposal the cable type A and type B will be used with the single gap and the dual gap magnet, respectively.

These novel cable and core designs are expected to substantially minimize the power losses due to eddy currents and magnetic hysteresis that are high for the rapid cycling accelerator magnets, which use the normal conducting (copper) power cables. They will potentially pave the way for the extended capabilities in magnetic ramp rate, lower required power and extend longevity in long-term operations.

The performance of the dual beam gap magnet will be compared to the single beam gap magnet in terms of the cable power losses and the complexity of magnet construction. Both test magnets will be coupled to the 500 Hz ringing mode power supply and to the 20 Hz white circuit power supply to achieve up 2000 T/s and 100 T/s ramp capabilities, respectively.

Relevance:
Rapid-cycling dipole magnets constitute critical components of many particle accelerator systems including the synchrotrons such as Booster, Main Injector and FAIR where the demand for the high beam intensities and the high repetition rate are essential for the successful physics programs. A successful R&D of the HTS-based rapid cycling magnets with a dual vertical beam gap will provide extended capabilities for the new synchrotron designs of the future Fermilab accelerator complex and other facilities within the DOE, as well as for the High Energy Physics facilities elsewhere, e.g. CERN in Europe, HEP in China.

Results and accomplishments:

- Engineering designs of HTS cables type A and B were completed including splicing connections to the current leads.
- Structural components of HTS cable type A were procured, fabricated and the cable was assembled.
- Engineering designs of both single gap and dual gap magnetic core were completed.
- Single gap magnetic core was fabricated, assembled and the cable type A installed inside the core.
- Laminations for the dual C-shaped magnetic core were procured, cut to a design shape, supporting components were fabricated and the core is being assembled.
- Engineering design of cryostats for both single gap and dual C-shaped magnetic cores were completed.
- Single gap magnet cryostat was fabricated and the magnet is installed inside the cryostat.
- Structural components of type B cable including connections to current leads were procured and submitted for fabrication.
- Cryogenic transfer line from MDB cryogenic plant to the test magnet area was constructed and installed.
- Single gap magnet is installed in the test area, connected to MDB cryogenic plant and to the power supply. The work on the magnet test system control electronics has begun.
- Safety review process has been initiated with the Fermilab Safety Group. A note describing magnet test system and the planned operations has been written. The FESHM 5031.1 Piping Engineering Note is in progress.

Publications:

A Milanese [1], H. Piekarz [2] and L. Rossi [1], "Concept of a Hybrid (NC + SC) Bending Magnet for (80-100) km Hadron/Lepton Colliders, TUOCB01, Proceedings of IPAC-2014, Dresden, Germany ([1] CERN, [2] FNAL)

Project Number and Title: FNAL-LDRD-2014-025
The Sinuous Target

Authors: (PI) Robert Zwaska

Project Description:

The project is to generate a new, engineered material for use in high-power accelerator targets. The sinuous material will be composed of a multitude of interlaced rills: wires of small dimensions. The sinuous bulk material will have improved resistance to thermal shock due to the very low effective modulus of elasticity. Furthermore, the interlaced nature of the wires makes it resilient to individual wire failures. The material will enable targets to accommodate higher incident beam power with more efficient secondary beam production. This project will develop production techniques of several matrixing approaches to the material, and test the mechanical and thermal properties of the engineered bulk.

Relevance:
A high-power target is an integral part of a neutrino beam, muon beam, other intensity frontier beams for high energy physics as well as neutron and rare isotope beams outside of high energy physics. Thermal, mechanical, and radiation effects limit the degree to which targets can be subject to high incident beam power. If successful, the material developed has applications at accelerators at Fermilab and within the DOE complex (including beam facilities for NP, BES, FES, and other areas). The most proximal application of this technology will be for the production of multi-megawatt neutrino beams at Fermilab.

Results and Accomplishments:
A fabrication technique for the sinuous material was identified to produce nanofibers of various materials on the appropriate scale. An electrospinning station is being developed at Fermilab to produce the sinuous materials. Various mechanical tests have been devised and will be used to compart the manufactured sinuous material to solid bulk material, as well as the previously identified bulk materials.

Publications:
The Sinuous Target, IPAC 2015, May, 2015. FERMILAB-CONF-15-261-AD

Project Number and Title: FNAL-LDRD-2015-009
High Energy Physics Pattern Recognition with an Automata Processor

Authors: (PI) Michael Wang, Christopher Green

Project Description:
This project investigates the effectiveness of the Micron Automata Processor (AP) in pattern recognition applications in High Energy Physics experiments (HEP). The major part of this project involves demonstrating a proof-of-concept based on a simplified computer model of the pixel detector of the Compact Muon Solenoid (CMS) experiment at the CERN Large Hadron Collider (LHC). The AP is used to find charged particle trajectories in the pixel detector associated with single, energetic electrons that potentially point to new and interesting physics. Upon successful completion of thus major phase, we will then focus on pulse shape recognition applications useful for track reconstruction in the Liquid Argon Time Projection Chambers (LArTPCs) of future neutrino experiments at Fermilab.

Relevance:
Pattern recognition is a fundamental task in HEP experiments that has become more challenging with each new generation of experiment and more difficult to address with conventional computing technologies as we approach the end of Moore's law. The Micron AP offers a unique solution based on a novel architecture ideally suited to such applications and which scales well to meet increasing demands. Being a commercial,

off-the-shelf product, it does not require the significant investments in capital and manpower that custom hardware solutions entail. A successful proof-of-concept demonstration based on the AP will provide the CMS experiment at Fermilab's Energy Frontier with a practical solution that will meet its growing pattern recognition needs well into the high luminosity era. It will also provide a future-proof pattern recognition solution for experiments like DUNE and Mu2e at Fermilab's Intensity Frontier.

Results and Accomplishments:
We have successfully completed the proof-of-concept demonstrating the feasibility of using the Micron AP for fast track pattern recognition applications in HEP experiments. Using the electron track confirmation application described above, we showed that the Micron AP was up to the task of identifying those rare collisions that produced single energetic electrons. By comparing it with traditional CPUs and GPUs, we also demonstrated that it could complete the demanding computation in significantly less time, making it a possible candidate for online applications with hard real-time constraints. A detailed description of these results has been published in the NIM journal (see Publications section below). Our project has been showcased in Fermilab's electronic poster at both the 2015 and 2016 Supercomputing Conferences. A presentation was also given at a special session arranged by Micron Technology during SC15. Our project is featured on Micron Technology's site (http://www.micronautomata.com/research - physics) and highlighted as a "member testimonial" on the welcome page of the University of Virginia's Center for Automata Processing (http://cap.virginia.edu). One of us was invited to present our research at the 25th International Workshop on Vertex Detectors held in September 2016 in Elba, Italy. Our results were also presented at the 22nd International Conference in High Energy and Nuclear Physics held in October 2016 in San Francisco.

Publications:
[1] M.H.L.S. Wang, G. Cancelo, C. Green, D. Guo, K. Wang, and T. Zmuda, Using the automata processor for fast pattern recognition in high energy physics experiments—A proof of concept, Nucl. Instrum. Methods Phys. Res. A 832 (2016) 219-230.

[2] M. Wang, C. Green, and T. Liu, Investigating the Micron Automata Processor for HEP pattern recognition applications, Proceedings of the 25th International Workshop on Vertex Detectors, September 26-30, 2016, La Biodola, Isola de Elba, Italy, PoS(Vertex 2016)045.

Project Number and Title: FNAL-LDRD-2015-020
Off-the-Shelf Data Acquisition System

Authors: (PI) Ryan Rivera, Kurt Biery, and Mark Bowden

Project description:
Define and evaluate a low-cost, scalable data acquisition (DAQ) system architecture based on commercial technology being developed for the emerging "Internet of Things"

(IoT). This approach connects intelligent front-end digitizers directly to a standard network without additional layers of custom readout electronics. The same network is used for data acquisition, event building, detector controls, online and offline data storage/processing, and control room interfaces. The system is scalable from a few MBytes/sec to hundreds of GBytes/sec using inexpensive commodity networking equipment and interface modules. The software will leverage already existing software developed at Fermilab to form a comprehensive data acquisition and processing infrastructure for current and future experiments. As part of this proposal we will include drivers for these generic network-attached digitizer interfaces. The goal is to define a complete and scalable "off-the-shelf" DAQ (*otsdaq*) system for use in a wide range of experiments and studies.

Relevance:
A wide range of experiments and studies rely on data acquisition systems that in the past were often based upon relatively expensive and short-lived technologies. As experiments are reluctant to subsidize the development of niche standards, an off-the-shelf DAQ enabled by the IoT has the potential to satisfy the requirements of a large range of experiments and studies at a very modest cost. We expect DAQ experts and novices to be able to re-use pieces of the *otsdaq* framework and make new contributions, in open source fashion, so that future DAQ work might be more efficient.

The *otsdaq* approach places an emphasis on scalability – so what works for you on your laptop in your office, can be replicated by an order of magnitude for your test beam run, and then again for your experiment – all managed through a user-friendly, web-based, graphical user interface and configuration system that grows with you as you go from one user to a full experiment of users.

Results and accomplishments:
We are into the last two months of the proposed two-year work plan for the Off-the-Shelf Data Acquisition System, and we have made good progress on the project's ambitious goals. We have surveyed the IoT market for candidate boards and selected a low-, mid-, and high-performance board (BeagleBone Black, PicoZed, and KC705 respectively) to populate the initial menu of supported hardware. We have developed and tested Ethernet firmware solutions for each of the boards on the initial menu. We have centralized the relevant source code into a common repository and compiler environment. We have launched a beta version of the public webpage that will be used to facilitate selections from the menu of supported *otsdaq* items. And, finally, we have launched the first stable release of the *otsdaq* software package (with an online introductory tutorial):

The web-based graphical user interface (GUI) on the client side is implemented in HTML5 and JavaScript. Web GUI functionality currently includes multiple-user management, chat, logbook, console message viewer, configuration GUI, 3D data visualizer, ROOT visualizer, state machine, and command macro creation/execution. The key advantage to the web-based user interface is that web browsers are available on all platforms and devices – users can control their DAQ system from a Linux node, a Windows PC, or their mobile device.

On the server side, *otsdaq* is implemented in C++, and makes use of the CERN XDAQ software framework for its web server, run control, and various utilities. *otsdaq* includes tools and templates for users to build custom components as plug-ins and integrate them into their system. *otsdaq* currently is compatible with Scientific Linux 6 and 7, and each *otsdaq* release will also be optionally available in the form of a Virtual Machine installation making your *otsdaq* system completely platform independent.

artdaq has also been fully integrated into *otsdaq*. *artdaq* is a *data acquisition toolkit* developed at Fermilab with core functionality in the areas of data transfer, event building, process management, system and process state behavior, control messaging, message logging, and configuration of software and hardware. *artdaq* makes use of the *art* event-processing framework providing experimenters a facility to perform the initial development and testing of their analysis and data quality monitoring modules in an offline context before moving them to the full online environment for final testing.

Current work on *otsdaq* includes slow controls and monitoring (including compatibility with EPICS), automated run control, user customizable GUIs, and documentation for additional tutorials.

Publications:
"otsdaq for Test Beam Infrastructure," Preston Hansen, et. al. ICHEP 2016. Poster presentation.

Project Number and Title: FNAL-LDRD-2015-021
Diagnostics for H- Beams Using Fiber Lasers and Synchronous Detection

Authors: (PI) Victor Scarpine, Jinhao Ruan

Project Description:
This research is to develop the concept of a combined transverse and longitudinal H^- beam profiling instrument utilizing a low-power, high rep-rate fiber laser with optical fiber transport to the accelerator and synchronous signal detection. Traditionally, beam profile measurements of H- beams is accomplished with high-power lasers and signal detection through the collection of electrons. However, a low-power laser will produce far fewer photo-disassociations and, hence, a smaller signal. This project will detect these small signal through narrow-band synchronous detection of a low-power modulated laser pulse train. In addition, this project will test the concept of acquiring these beam profiles by measuring reduction in H^- beam current, as opposed to electron collection. The final goal of this proposal is the construction and operation of a R&D profiling instrument that can study low-power photo-disassociation signals and laser and instrumentation systematic issues, as well as make initial beam profile measurements.

Relevance:
Beam profile measurements in high-intensity, superconducting H^- accelerators are driving the need for non-invasive measurements of both transverse and longitudinal profiles. The technique of photo-disassociation of H^- is generally the technique used for

non-invasive profile measurements. Usually this requires the use of high-power, low rep-rate lasers, increased beam line space and complicated light transport systems which lead to slower profile measurements, higher costs and accelerator and laser safety issues.

The beam profiling technique of this project has a number of new and novel features. The primary advantages of this approach are:

1. Safer and easier transport lower-power laser light, with optical fibers, through the accelerator system with no risk of damage to optical vacuum windows.
2. A combination of both transverse and longitudinal profile measurements in one system.
3. The use of amplitude modulation of the laser pulse train with synchronous lock-in amplifier detection and oversampling techniques, which will enable the detection of the very small signals and faster profile measurements.
4. The measurement of profiles, by a reduced beam intensity method, which will allow for minimizing the required accelerator beam line space by removing the requirement to collect photo-disassociated electrons.

Results and Accomplishments:
This project requires several specific components to be design and constructed before assembly into the final beam profile measurement system. This past year of the project has focused on completing designs and acquiring many of these key components. Design of the two-watt Ytterbium fiber laser has been completed, vendor selection has been made and acquisition of the laser is underway. Design and layout of the free-space scanning optics is proceeding. Modelling of the magnetic field necessary for electron collection is complete, as well as choice of electron collector electronics. The completion of these component designs has allowed the beamline vacuum chamber design to be finalized and will soon proceed to construction.

The intended test accelerator, PIP2IT (Proton Improvement Plan II Injector Test), has successfully delivered 2.1 MeV H^- beam, that will be used for beam measurements for this project. In addition, much of the necessary PIP2IT infrastructure needed for this project are proceeding. The PIP2IT laser hut design is complete and ready for construction.

Overall, effort on the project has continued but at a reduced pace due to manpower limitations. The integration of components into the final system is proceeding with the goal to produce measurement results at PIP2IT in 2017. The key deliverables for this project will be the construction and operation of a test fiber laser based beam profiler and initial beam measurements. This profiler will be available for future testing and development beyond this project.

Publications:
There have been no publications for this research at this time.

Project Number and Title: FNAL-LDRD-2015-031
A comprehensive investigation of a transformational integrable optics storage ring as a "smart" rapid cycling synchrotron for high-intensity beams

Authors: (PI) Alexander Valishev

Project Description:
This proposal seeks to enhance Fermilab's strategic vision via engaging in a comprehensive feasibility study and investigation of an integrable optics "smart" rapid cycling synchrotron (RCS) as an essential component of a potential future multi-megawatt (MW) facility to advance neutrino science. The high-level project objective over a 3-year period is a full analytical, computational and technical evaluation of a scenario for multi-MW neutrino facility based on an innovative high intensity RCS.

Relevance:
A future multi-MW accelerator would be an enabling new device for research at the forefront of the intensity frontier with possible application to high luminosity hadron machines at the energy frontier. If successful, the study will result in significant cost reduction for a planned new RCS aimed to attain the beam power more than 2 MW for the future long baseline neutrino program.

Results and Accomplishments:
The first-year objectives were to a) develop and optimize the possible scenarios for multi-MW facility; b) develop tools and establish procedures for modeling of the particle dynamics in an RCS. Following this plan, the beam power available at 120 GeV in the Main Injector was parameterized as a function of integrable RCS machine properties. Two scenarios were developed and optimized to achieve the beam power of 3.6 MW in the Main Injector: i) baseline, with an RCS, which can sustain a Laslett tune-spread of -0.51 at the injection energy of 0.8 GeV, and a ramp rate of 12 Hz; ii) alternative, with a modest Laslett tune-spread of -0.27, injection energy upgraded to 1.2 GeV, and a ramp rate of 40 Hz. Both scenarios would be a powerful upgrade over the PIP-II Fermilab Booster, which can only support 0.5 MW in the Main Injector without relying on slip-stacking. The designs use realistic magnet field strength and accelerating RF system requirements. Along objective b) the baseline scenario parameters were used to develop a lattice design that synthesizes the requirements for integrable optics with features of a modern RCS. Beam dynamics simulations using Synergia code with space-charge forces were initiated, and the space-charge tune depression was verified to match its predicted value. The results of these studies were reported at two major accelerator conferences: the Advanced Accelerator Concepts Workshop, and at the North American Particle Accelerator Conference.

Publications:
J.S. Eldred and A. Valishev, "Integrable RCS as a proposed replacement for Fermilab Booster", in Proceedings of AAC2016, Washington, DC (2016)

J.S. Eldred and A. Valishev, "Design Considerations for proposed Fermilab Integrable RCS", in Proceedings of NAPAC2016, Chicago, IL (2016).

E. Prebys et al., "Long Term Plans to Increase Fermilab's Proton Intensity to Meet the Needs of the Long Baseline Neutrino Program", in Proceedings of IPAC2016, Busan, Korea (2016).

Project Number and Title: FNAL-LDRD-2016-001
Beam Precision Time Profile Monitor

Authors: (PI) Eric Prebys, Dave Hedin

Project Description:
The goal of this project is to measure the fraction of beam that falls outside of nominal beam bunches, with a sensitivity of at least 10^{-5}. The general problem of such measurements is the large dynamic range required to directly measure the beam intensity. Our proposed technique uses a statistical method, in which a charge telescope is used to monitor beam scattering off of an existing multi-wire or multi-foil installed in the beam line. An accurate time profile will then be built by integrating over many bunches. The sensitivity is expected to be at least two orders of magnitude better than that which can be achieved with traditional techniques, such as resistive wall monitors. We will initially use the Recycler primary collimators to scatter particles, to evaluate the 2.5 MHz Recycler bunches. The detector consists four arms of four detectors each. The sensitive element of each detector is a 1" cube of Quartz, which will generate Cherenkov light when a charged particle passes through. Cherenkov light is used because it is insensitive to soft backgrounds, and does not suffer from the "afterglow" problems of scintillators.

Relevance:
Longitudinal beam tails have significant implications for beam and acceleration efficiency, and are therefore an important consideration for all experiments where beam loss is a factor. At Fermilab, this will be particularly important as we increase the intensity of the Main Injector in the coming years. In the near term, this measurement is important to the Mu2e Experiment, which has very stringent limits for out-of-time beam. This detector will use the Recycler beam scrapers to scatter particles, to evaluate the 2.5 MHz Recycler bunches. The results can be directly compared with simulations, which is in itself of fundamental interest to the accelerator community. These measurements will also provide valuable insight into Recycler operation for future experiments.

Results and Accomplishments:
We assembled the first arm of the spectrometer and tested at the Fermilab Test Beam Facility last summer. Those tests established that the sensitivity is more than adequate to form four-fold coincidences for highly relativistic particles, and that noise and after-pulsing are low enough that accidental coincidences will not be a problem. We later installed the spectrometer in the Recycler, positioned to see scatters from the newly installed primary collimator. We have shown that we can observe beam scatters from the 53 MHz slip-stacked beam for NOvA operation, and we will be able to full exercise the

system when the Accelerator Division begins making 2.5 MHz bunches for g-2 operation. All parts for the remaining three arms have been requisitioned, and the rest of the detector will be assembled when they arrive.

Publications:
Results from the summer beam test were written up in Fermilab BEAM-DOC-5221. We will publish in PR-STAB or NIM when we complete our Recycler tests.

Project Number and Title: FNAL-LDRD-2016-004
Development of an ultra low energy threshold particle detector

Authors: (PI) Javier Tiffenberg, Yann Guardincerri, Christopher Bebek, Jeremy Mardon, Rouven Essig, Tien-Tien Yu, Tomer Volansky

Project Description:
This project seeks to advance the development and construction of a prototype new generation CCD-based particle detector with an ultra low-energy threshold. We have successfully build the first instrument with discrete sub-electron counting capability that can be reproducibly achieved over millions of pixels on a stable, large-area sensor. This leap in technology allow us, for the first time, to to reach the absolute theoretical limit of 1.1 eV in energy threshold, set by the silicon band gap. The sensor is pixelated with a spacial resolution of 15 micron and is capable of discriminating and counting individual electrons on each of its 4 million pixels.

This innovative readout technology has a negligible impact on CCD design and fabrication, and can have nearly immediate implications for a wide range of scientific disciplines, from biological imaging to fundamental physics. Specifically it has immediate applications on neutrino and DM direct detection experiments.

Relevance:
The energy threshold of 50 eV of existing detectors precludes access to very low energy interactions. By reducing the energy threshold to 1.1 eV we are now able to investigate a new regime of interactions and provide the technology needed to build the next generation of neutrino and Dark Matter (DM) experiments that will be at the forefront of exploring physics beyond the Standard Model. We are planning to build a larger version of our prototype system to conduct the first search of DM using this technology and explore a large number of currently inaccessible physics theories that are beyond the Standard Model of Particles.

We are also exploring imaging applications that could have a major impact in astronomical instruments and microscopy.

Results and Accomplishments:
We have already accomplished the primary objective of the project by successfully building the first instrument with discrete sub-electron counting capability that can be reproducibly achieved over millions of pixels on a stable, large-area sensor. We are currently on the process of deploying one of such systems at the MINOS underground

facility, a shallow underground laboratory located on Fermilab grounds. This effort will allow us to completely validate and demonstrate the technology for DM and neutrino experiments. By the end of the project at FY17 this objective will be completed.

Publications:

* SENSEI Collaboration. “Single-photon counting over a large dynamic range with silicon Skipper-CCDs”, paper in preparation (2017)
* SENSEI Collaboration. “Skipper-CCD sensors for light-DM searches”, paper in preparation (2017)
* SENSEI Collaboration. “Ultimate measurement of the Fano factor in Silicon by counting individual electrons ”, paper in preparation (2017)

Project Number and Title: FNAL-LDRD-2016-007
Tuning Axion Detectors with Non-Linear Dielectrics

Authors: (PI) Andrew Sonnenschein, Daniel Bowring, Shashank Priya

Project Description:
Our LDRD proposal focuses on exploiting the novel electronic properties of non-linear dielectric materials such as strontium titanate ($SrTiO_3$) to build more sensitive detectors for axion dark matter particles. The expected properties of axion particles make them extraordinarily difficult to observe, as their interactions with ordinary matter and light would be negligible. However, in the presence of intense magnetic fields, axions may convert into ordinary photons, producing a weak electromagnetic signal that could be in principle be observed. Detection of this signal will require large arrays of microwave resonator structures precisely tuned to a common frequency. The existing schemes for doing this require a large number of mechanical actuators operating at a temperature of just a fraction of a degree above absolute zero. Our proposed scheme would greatly simplify the problem by substituting solid state electronic tuning elements for mechanical actuators, making possible detectors with orders of magnitude larger detector volume and greater sensitivity.

Relavance:
It is remarkable that in the first decades of the 21st century, we still do not understand the particle nature of the most abundant type of matter in the universe, the so-called “dark matter”. One intriguing possibility is that the dark matter is composed of particles called axions, originally proposed to explain inconsistencies in the theory of the strong interaction of quarks and gluons (quantum chromodynamics). The long term goal of our research program is to discover the nature of the dark matter. This goal fits squarely within the mission of DOE’s Office of High Energy Physics and within the Fermilab experimental program. Fermilab is currently the lead lab for the ADMX-G2 axion search experiment. The technology we are developing maybe used to extend the sensitivity of this experiment or similar future projects.

Results and Accomplishments:
We have successfully deposited high quality, micron-thick films of $SrTiO_3$ dielectric on quartz and sapphire substrates. A cryogenic dielectric probe has been built to measure dielectric properties of films at frequencies of 4- 7 GHz and temperatures down to 2 Kelvin in a magnetic field of up to 7 Tesla. The probe contains a small coplanar waveguide resonator designed using the ANSYS HFSS finite element electromagnetic simulation code. Initial measurements with this resonator cell have confirmed its expected performance. We've used the cell to collect data from our $SrTiO_3$ films and demonstrated the use of dielectric films to shift the frequency of the resonator. We're now preparing for measurements with an electric field bias to show that the non-linear characteristics of $SrTiO_3$ can be used to tune the frequency.

Project Number and Title: FNAL-LDRD-2016-008
Novel Methods for High Performance Superconducting Coating on Copper

Authors: (PI) Genfa Wu

Project Description:
Superconducting thin film cavities have the potential to save tens of millions of dollars in materials costs for superconducting accelerators. This project seeks to develop innovative approaches to generate superconducting coatings on cheaper substrate such as copper cavities that will match or exceed performance of bulk niobium cavities. The unique approach of this proposal is to dramatically increase film's thickness using high quality high-speed deposition to achieve a film that is in the range of 50-100 micron in thickness. When using after-coating furnace annealing and chemical etching, one can truly obtain a coating that is closer or better than bulk material.

Relevance:
As the copper based film cavity performs, no one will ever make SRF cavities using expensive solid niobium. The film cavity will be able to take advantage of the very high thermal conductivity of the materials such as copper that can support high gradient operation more easily. The practical importance of the film-based cavity is the cost savings, where copper costs less than a tenth of that of niobium. The successful outcome of this R&D project can directly benefit future HEP particle accelerators such as Proton Improvement Project (PIP3). If PIP3 will be built based on bulk superconducting technology, then it is estimated that ~ $20M of niobium material will be needed. If SRF cavities could be built with comparable performance out of microns' thick niobium films on copper, then the cost savings would be of the order of $15M just for the PIP-3 project. Another example of important application for this technology would be Future Circular Collider (FCC) that would need significant more niobium material compared to PIP3. The benefit of coated cavity extends beyond the high energy physics that includes other department of energy programs such as nuclear energy physics, basic energy science as well as particle accelerators for industrial applications.

Results and Accomplishments:
1. Major components for ECR coating are in place.

Vacuum system and magnet system for coating have been designed and fabrication is in progress. Electron beam source for electron cyclotron resonance plasma has been obtained from collaborators such as Cornell University and Jefferson Lab. RF system is being procured.

2. HiPIMS Design
   Vacuum system is shared with ECR coating. And its design is completed. Magnetron prototype design is completed and a journal paper is submitted. Optimization is in progress.

Publications:
A Computational Model for Magnetron Sputtering Devices using VSim, submitted for JVST, JVST A Paper Number: AVS63JVSTA-A-17-030, jointly authored with James D. McGugan of Tech-X.

Project Number and Title: FNAL-LDRD-2016-010
Preparing High Energy Physics (HEP) reconstruction and analysis software for exascale-era computing

Authors: (PI) Marc Paterno, Christopher Green

Project Description:
The project is to produce a prototype software system suitable for moving high energy physics (HEP) experiment event data through multiple processing stages in an exascale-class computing facility. There are two critical components to be demonstrated: a) high-performance input and output (I/O) to a parallel filesystem and b) communication of event data through node interconnects rather than through the filesystem. Simulated and experimental HEP data will be used for the I/O implementation studies, the data store methods for a high-core-count, low-memory per core system, and studying the scaling performance.

Relevance:
HEP experimentation requires advanced computing capabilities and often breakthroughs in experimentation are the result of advances in computing. Current HEP projects take advantage of "high throughput computing" (HTC) which utilize an architecture not compatible with the new "high performance computing" (HPC) machines that will make available factors of 10s and 100s more processing power. This project will perform research and development on the architectures required for HEP data to make use of HPC machines.

Results and Accomplishments:
In the first year, we focused on the encoding of HEP data into several formats, based on the Hierarchical Data Format (HDF5) system. HDF5 is developed and maintained by the HDF Group, and is the premier data file format used at HPC centers. It supports parallel filesystems (which are in use at all large HPC centers) and parallel I/O. We drafted a Fermilab technical publication enumerating the several processing contexts in which HEP I/O is required, identifying the majority of contexts which require event-by-event reading

(as opposed to analysis contexts, in which small parts of events are read). Using quick prototype Python implementations, we evaluated multiple organizations for the run/subrun/event/data product hierarchy, and chose two for further development and performance characterization in C++. We also worked with the HDF Group to identify three data products, from the Deep Underground Neutrino Experiment (DUNE), which span the range of complexity of such products.

We have also begun the investigation of a distributed C++ runtime system, Charm++, to evaluate its suitability for use as a basis of an HEP event-processing framework. Charm++ has been used in a variety of traditional HPC problem domains. We have met with the main the Charm++ designers to discuss possible program organization, and are now working on the first demonstration of a conceptual HEP event-processing framework using Charm++.

Publications: Fermilab technical publication on event storage requirements, being prepared.

Project Number and Title: FNAL-LDRD-2016-032
Implement open source High Energy Physics (HEP) Non Structured Query Language, NoSQL, database

Authors: (PI) Jin Chang (Fermilab), Igor Mandrichenko (Fermilab), Oliver Gutsche (Fermilab), Jim Pivarski (Princeton University)

Project Description:
Efficient management of "big data" is critical to the overall success of many high energy physics experiments at Fermilab. From the initial event reconstruction to data analysis, scientists spend much time in sorting out the computing details of selecting and correlating interesting events before being able to extract physics results. The time it takes to reach the point of result extraction is directly correlated to the expediency and magnitude of the physics harvest of an experiment. Shortening the time results in more science done more quickly.

The purpose of this project is to implement an open source HEP NoSQL database and computing framework that can be used as a broader data analysis service for multiple HEP experiments. We believe such a platform will offer greater flexibility and significantly reduce the overall efforts required for data analysis than currently used file-based technologies. In addition, the proposed platform will further establish Fermilab as a valued participant in Big Data R&D and is well aligned with the upcoming research direction led by DOE ASCR in the areas of exascale science.

Relevance:
One of the main challenges in managing high energy physics data is making the data accessible to a large number of data analysts with different interests. The dataset is large, but also generic because it contains information for any possible analysis. Every data analyst must therefore filter and transform the data in different ways. Moreover, this

process has to be repeated many times to find optimal data selection criteria to produce the most accurate physics results.

Given this challenge, most physicists resort to making private copies of the data with fewer events ("skimming") and/or fewer variables ("slimming") than the original dataset. This compounds the problems of computing resource utilization and data versioning and provenance. Our goal is to short-circuit this process with a responsive query system that quickly finds and serves physics data on demand, eliminating the need to copy data.

We are doing this by storing the data into a NoSQL database, with several layers of in-memory cache and providing a mechanism to find and deliver relevant data to the analysis process in a columnar data representation.

Results and Accomplishments:
In FY16, we have achieved several milestones in designing a HEP data analysis platform – (1) determined high-level data analysis scenarios such as data skimming and derivations of data of the CMS experiment (use case: a CMS dark matter analysis); (2) defined a flexible mapping scheme to a columnar NoSQL data store to persist physics analysis objects; (3) determined a standard set of interfaces for user interaction (data lookup and retrieval queries); (4) defined details of technical components for analytics computing and data storage.

Project Number and Title: FNAL-LDRD-2016-034
R&D and Experimental Instrumentation for the Initial Set of Critical Scientific Experiments in IOTA and the FAST Injector

Authors: (PI) Swapan Chattopadhyay

Project Description:
An experiment with a proton/ion beam will be to understand how such a beam behaves in the Integrable Optics Test Accelerator (IOTA) ring given that it is space-charge dominated. For this experiment to be done, the injection line will be instrumented with diagnostics such as beam position monitors and beam loss monitors that are special purpose to IOTA. A second experiment involves an pencil-like electron beam that tightly controlled in order to understand the optical properties of the IOTA ring. This experiment will require some special-purpose optical elements and very fast photo detectors. The LDRD project is to procure the above special-purpose equipment to enable the first set of experiments to be conducted.

Relevance:
The IOTA and FAST accelerators have been chosen as test accelerators to help pave the way to develop much more intense beams than have been done before. Such beams are required for future experimentation in high energy physics including neutrino physics. As such, this LDRD project is tied to the mission and strategic future of Fermilab.

Results and Accomplishments:
Note: This project, while previously approved, incurred no costs in FY16 and the project will start beginning in FY17.

VI. Notes on Completed Projects

Each Fermilab LDRD project that is completed will have a Final Report written and submitted to the DOE Office of Scientific and Technical Information.

VII. Conclusions

Fermilab is successfully conducting a LDRD program in accordance with the terms of its authorization. The current portfolio of approved projects are addressing R&D in several areas of scientific and technical expertise that exist at the Laboratory. All projects are aligned with the mission of the Laboratory and DOE and have begun to making good progress. Already, there have been several publications that are related to the LDRD work and a provisional patent that has been generated. The number of proposals already submitted and subsequent discussion with those who have submitted the proposals also indicate that the LDRD program is strengthening the scientific and technical vitality of Fermilab.